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GAMMA-RAY TRANSITION ENERGY CORRELATIONS IN ^{156}Er AND ^{160}Yb

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Extensive studies[1,2] of the rotational nucleus ^{160}Yb have shown the presence of two backbendings in the yrast line, as well as the existence of irregularities in the side bands. The interpretation of the level scheme in terms of bandcrossing[2] has been very successful. The nucleus ^{156}Er, whose yrast band[3] is very similar to that of ^{160}Yb up to spin 24 $\hbar$, has been shown[4] to exhibit a sharp second backbending. This second irregularity has been interpreted as being most likely due to a neutrons effect. In order to complement the studies of the discrete lines, we looked at the γ-continuum via the γ-γ energy correlation technique described by B.Herskind[5].

The two nuclei ^{160}Yb and ^{156}Er were respectively produced in the heavy ion fusion reactions $^{148}Sm + {}^{16}O$ at E_{inc} = 105 MeV and $^{141}Pr + {}^{19}F$ at E_{inc} = 100 MeV. In both reactions the 4n channel is prominent with ≃ 84 % of the total cross section for the production of ^{160}Yb and ≃ 70 % for ^{156}Er ; the percentage for the 3 and 5n exit channels are respectively ≃ 16 % for ^{161}Yb and 15 % for $^{155,157}Er$. The maximum angular momentum brought into the compound nucleus calculated according the formula deduced by Baas[6] for a liquid drop is 52 $\hbar$ and 51 $\hbar$ respectively.

To record the γ-γ coincidence matrix, a set of three Ge(Li) detectors was used. The detectors were carefully chosen with nearly the same response function and their gain properly matched to be able to sum all the three possible γ-γ combinations. In the resulting coincidence spectra, only a small percentage of the total number of events is due to photopeak x photopeak coincidences, the rest being due to Compton scattered events. In order to remove the Compton background from the spectra two methods can be applied. One consists of unfolding the two dimentional Ge(Li) x Ge(Li) spectra, after a scrupulous study of the response function of each detector in situ. This procedure is now operating but is very time consuming for the computer. A second method[5] calculates the deviation ΔN_{ij} from the average coincident rate. This method does not yield the absolute counts value, but enables the structure of the γ-γ coincidence field to be reproduced quite easily. It has been applied in the present study.

In fig. 1 and 2, to enhance the gross structure observed in the two dimentional correlation spectra, the energy resolution of the detectors has been artificially deteriorated from 2 keV to 20 keV. This procedure gives more evident spectra, but one loses information for the fine structure. For that reason, the results obtained for different slices perpendicular to the 45° diagonal are taken from the real correlation spectra.

The valley along the diagonal observed in these spectra is the signature of the rotational behaviour of the nuclei. The width W of the valley is directly related to the "collective" moment of inertia $\mathcal{J}_c$, that is the moment of inertia which corresponds to a rotational band, by the relation $W = 16\,\hbar^2/2\mathcal{J}_c$.

F.S. Stephens et al[7] have shown that for intermediate nuclear deformation (β~0.2) and for one or a few particles in a high - j shell, a coupling scheme where j is quantized along the rotation axis is valid (Rotational Alignment). The following energy spec-

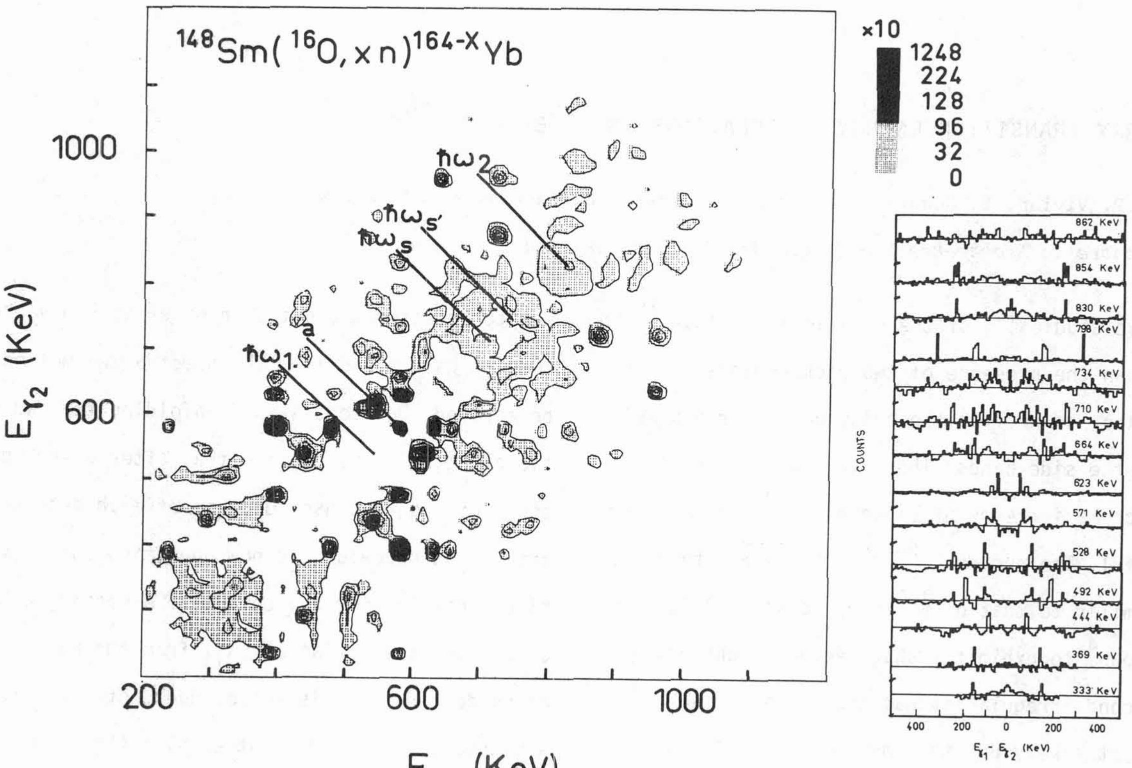

Figure 1 : *Positive correlation spectrum ΔN_{ij} for ^{160}Yb and corresponding projections perpendicular to the diagonal. For each slice the mean energy value $(E_{\gamma 1} + E_{\gamma 2})/2$ is indicated. $\hbar\omega 1$ and $\hbar\omega_2$, $\hbar\omega_s$ and $\hbar\omega_s{}'$ are the backbending frequencies in the yrast band and side bands respectively.*

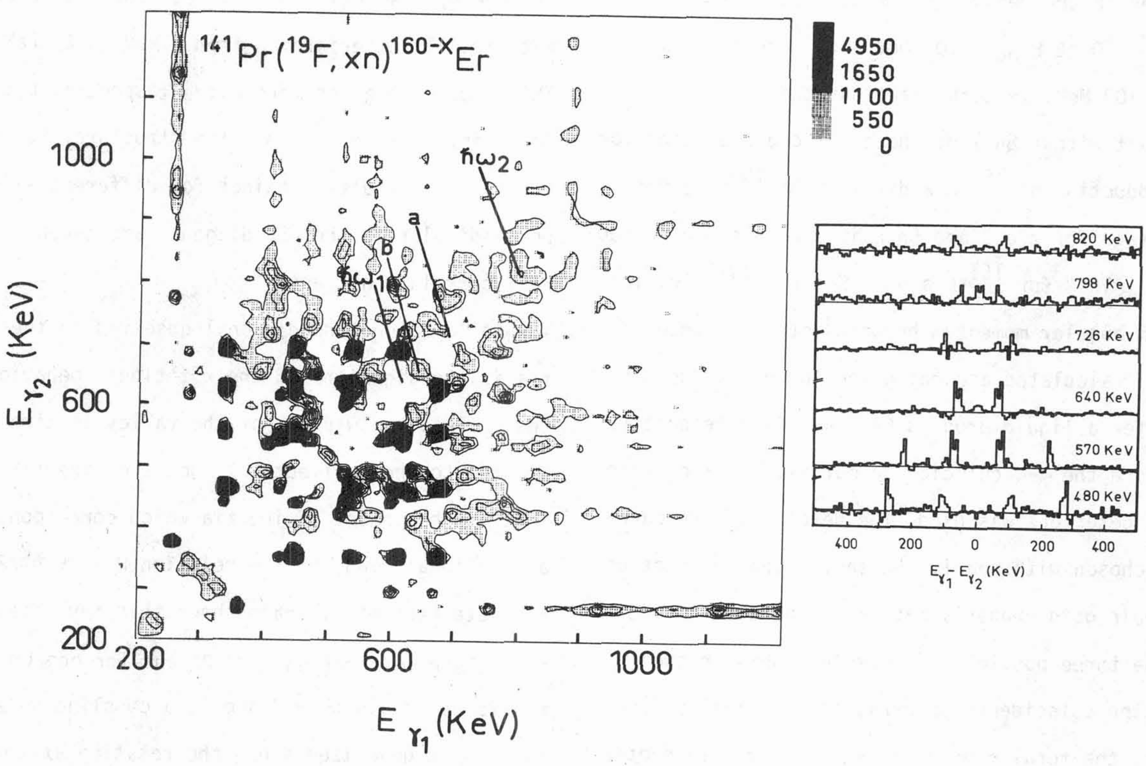

Figure 2 : *same as in Figure 1 for ^{156}Er.*

trum is then obtained $E \simeq e_{ja} + \frac{\hbar^2}{2\mathcal{J}_c}(I-ja)^2$ where j_a represents the aligned angular momentum along the rotation axis and e_{ja} is the single particle energy. The transition energy within a band is :

$E_\gamma = \frac{\hbar^2}{2\mathcal{J}_c} 4(I-j_a) \simeq 2\hbar\omega$ (1). From the $\gamma-\gamma$ correlation spectra one can deduce an average value of $\mathcal{J}_c$ corresponding to several bands with different j_a. Figures 1 and 2 display the bidimensional correlated spectra obtained for ^{160}Yb and ^{156}Er, together with different slices perpendicular to the 45° diagonal. The valley can be followed up to $\simeq$ 870 keV for ^{160}Yb and to 920 keV for ^{156}Er. For low energy transitions, up to ~ 500 keV, the observed narrowing of the valley for ^{160}Yb with increasing energy reflects the behaviour of the ground band moment of inertia below the first backbending. Beyond the first backbending up to 750 keV, the width of the valley remains almost constant. The ridge which is narrow below the first backbending becomes wider, indicating a spread in the moment of inertia. One can then represent the yrast like decay by several collective bands with different moments of inertia corresponding to various degrees of alignment of the single particles. The discontinuities observed in the different bands of the discrete spectra, shows up in the $\gamma-\gamma$ correlation spectra as a filling of the valley. In both nuclei, the first backbending is very sharp and therefore does not cause any filling at the proper frequency. Instead one observes a filling of the valley in ^{160}Yb at a point corresponding to the transitions : 589 keV ($8^+ \rightarrow 6^+$) and a 586 keV ($12^+ \rightarrow 10^+$) and in ^{156}Er to the transitions : 682 keV ($12^+ \rightarrow 10^+$) and 710 keV ($20^+ \rightarrow 18^+$)(see point noted a in the figures). In ^{160}Yb, two strong bridges appear ($\hbar\omega_s$, $\hbar\omega_s$') and correspond to the frequencies of the discontinuities observed in the side bands. The bridge marked b in ^{156}Er corresponds to the coincidence between two transitions 643 keV and 639 keV observed in one of the side bands.

At $\hbar\omega$ = 0.40 MeV in ^{160}Yb and 0.38 MeV in ^{156}Er the valley is totally filled up. At higher energy the valley appears again and vanishes around 870 keV and 920 keV respectively. The fact that these structures in the valley are very pronounced is understood in terms of multi-band crossing, i.e. the fact that many bands are expected to experience crossings at the same frequencies as the irregularities observed in the discrete spectra. In order to reproduce the effect of a multi-band crossing, we have constructed a computer simulated $\gamma-\gamma$ spectrum assuming that the different bands experience a crossing around the same frequency $\hbar\omega$ = 0.39 MeV. In this simulation we have used realistic detector response functions to construct the $\gamma-\gamma$ two dimensional coincidence spectrum. Then we have applied the data reduction technique discussed before to extract the corresponding correlated spectrum. Figure 3 displays the correlation spectrum resulting from such a simulation for ^{160}Yb.

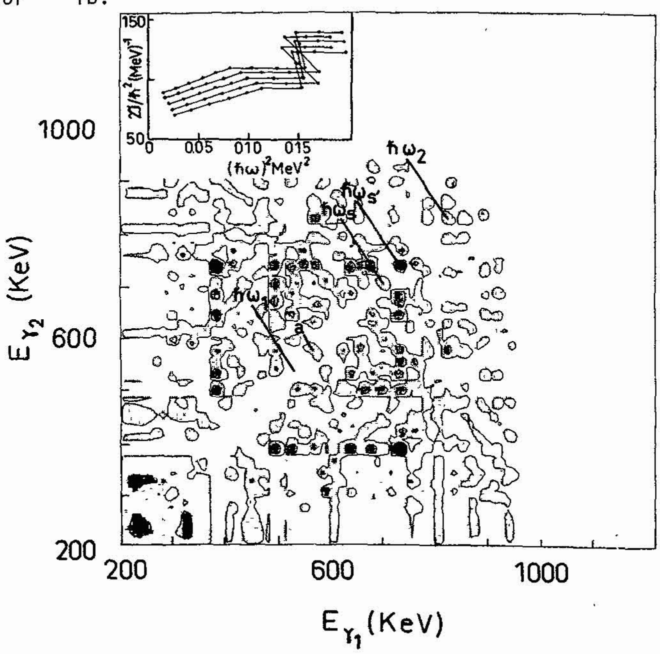

Figure 3 : Simulated positive correlation spectrum ΔN_{ij} for ^{160}Yb.

The discrete lines have been included with their proper intensity as deduced from the experimental data. Some of the bands used in the calculation are shown in a backbending plot in the upper left part of figure 3.

The observed end point of the valley (Fig.1,2) is related to the energy of transitions de-exciting the highest spin collective states fed in the reaction. The corresponding moments of inertia deduced from the width are 136 ± 18 $(MeV)^{-1}$ for ^{160}Yb and 111 ± 22 $(MeV)^{-1}$ for ^{156}Er. The maximum angular momentum at the top of the yrast cascade is evaluated to be $I \approx 44\,\hbar$ for both nuclei. We assumed that each neutron takes away 1.5 $\hbar$ and that 4 statistic γ-rays de-excite the nuclei towards the yrast region each taking away 0.5 $\hbar$ [8]. Using relation 1, the corresponding single particle aligned angular momentum is found to be $\approx 15\,\hbar$ for ytterbium and $\approx 17\,\hbar$ for erbium. These values are in good agreement with the aligned angular momentum deduced from the discrete spectra beyond the second backbending : it has been evaluated to be 17 $\hbar$ in ^{156}Er and at least 15 $\hbar$ in ^{160}Yb.

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